The Determination of Cloud Altitudes Using GOME Reflectance Spectra: Multilayered Cloud Systems

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Abstract—This paper is devoted to the application of the Semi-Analytical Cloud Retrieval Algorithm (SACURA) to the cloud-top height determination using data from the Global Ozone Measurement Experiment (GOME) instrument onboard Earth Remote Sensing satellite (ERS-2). In particular, measurements of the top-of-atmosphere reflectance in the oxygen absorption A-band are used. The technique is based on the asymptotic radiative transfer theory as applied to studies of the oxygen absorption bands in reflected light. Our approach is valid for optically thick clouds with cloud optical thickness larger than approximately 5. The accuracy of the algorithm is checked against independent retrieval techniques for completely cloudy pixels. In particular, the close coincidence with data obtained from the Along Track Scanning Radiometer (ATSR-2) onboard ERS-2 is found. Some results of retrievals using these different instruments disagree (up to 2 km). This is explained by the strong horizontal inhomogeneity of clouds under investigation, which is not accounted by the SACURA or, possibly, by well-known problems of infrared techniques as applied to low-level clouds. The effective cloud geometrical thickness l is also retrieved. This parameter is defined as the geometrical thickness of a vertically homogeneous cloud, which allows for the minimization of differences between observed and calculated top-of-atmosphere reflectance spectra. For inhomogeneous clouds, the value of l differs from a real cloud geometrical thickness, but it gives us an indication of the possible existence of the multilayered cloud system in the field of view of the optical instrument.

Index Terms—Clouds, radiative transfer, remote sensing, spectroscopy.

I. INTRODUCTION

MOST OF THE modern satellite-based spectrometers and radiometers have a capability to get information on a cloud-top height distribution on a global scale [6]–[10], [14], [17]–[19], [26]. As far as measurement techniques and retrieval methods are concerned, they differ considerably both in terms of their theoretical basis and accuracy, depending on the instrument. They range from active measurements, using lidars and radars on satellite platforms [20], to passive techniques, based on the processing of information, contained in the thermal infrared radiances [7] or reflected light polarization [8]. Stereo photogrammetric methods [16] and methods based on the measurements of the top-of-atmosphere (TOA) reflectance in

the oxygen A-band [10], [17] are also very popular techniques nowadays.

The subject of this paper is the first application of the improved oxygen A-band-based cloud-top height retrieval technique developed by Rozanov and Kokhanovsky [24] to the Global Ozone Monitoring Experiment (GOME) measurements.

The physics behind the technique is quite simple. Indeed, let us assume that we have a gas in a planetary atmosphere, which absorbs almost all incident radiation in a narrow spectral band. Then, the difference in the reflection between wing and center of this band (depth of a band), measured by a receiver on a satellite orbiting the planet, will depend on the cloud altitude. Gas concentrations generally decrease with the distance from the ground. Clouds at a high altitude do not allow photons to penetrate to low atmospheric layers and be absorbed there. So, the depth of a spectral band will decrease, if clouds are present in the field of view of a sensor.

However, the absorption of photons takes place not only in the atmosphere above the cloud but in the cloud itself, too. This leads to the enhancement of the absorption. Thus, the depth of the absorption band depends both on the cloud altitude and the cloud geometrical thickness.

Indeed, the very first results of the cloud-top height retrieval from the measured reflectance spectrum in O_2 A-band [25] have shown that this enhancement of the absorption has to be taken into account to derive an accurate value of the cloud-top height.

Therefore, the proposed Semi-Analytical Cloud Retrieval Algorithm (SACURA) allows for the retrieval of both the cloud-top height h and the effective cloud geometrical thickness l simultaneously. This is the main new feature of the SACURA as compared to other cloud retrieval techniques. Note that the retrieved value of l corresponds to the case of a homogeneous cloud layer. Therefore, it can be considerably biased as compared to a sum of the geometrical thicknesses of cloud layers in multilayered cloud systems. However, the account for the effective value of l increases the accuracy of the cloud-top height retrieval (see below).

The solution of the inverse problem is very complicated in the case studied. Popular lookup-table techniques are not applicable due to a large number of parameters involved. The minimization techniques based on the exact solution are very time consuming. They do allow for single runs but cannot be considered as an option for operational retrievals, due to the computation speed constrains.

For that reason, our retrieval algorithm uses the approximate analytical solution of the radiative transfer equation given by Kokhanovsky and Rozanov [11] to speed up the retrieval considerably. This is another new feature of the SACURA.

As it follows from our theoretical studies [24] the accuracy of the SACURA is quite high for homogeneous cloud layers. It was also established that the vertical inhomogeneity of clouds such as vertical profile of liquid water content and especially multilayered cloud systems can influence the accuracy of the retrieval considerably. The maximal errors of the determination of the cloud-top height occur if the observed cloud field is remote from the homogeneous assumption made in the forward model (e.g., the presence of multilayered clouds). The retrieved value of l can be in such cases so large that a homogeneous cloud must have a value of the geometrical thickness larger than h. This points out to the fact that the retrieved geometrical thickness can be used as a quantitative criterion to judge whether our homogeneous assumption corresponds to the real atmospheric situation.

Note that the retrieved cloud-top height does not give any indication on the correspondence of the forward model to a real atmospheric situation. Most modern retrieval techniques have this weak point.

The performance of our semianalytical cloud retrieval algorithm is highly dependent on the characteristics of the instrument used. In particular, high spectral and spatial resolution in oxygen A-band is needed. Unfortunately, such data are not available to us. An instrument [the Orbiting Carbon Observatory (OCO)] to fully explore possibilities of our technique has been already designed [2], [13]. It has $1.0 \times 1.5 \text{ km}^2$ spatial resolution. The resolving power of the OCO is equal approximately to 17 500. It translates into approximately 0.04 nm for the spectral resolution. However, the OCO was not launched in space so far. So, we used TOA reflectance measurements from the GOME instrument [1] onboard Earth Remote Sensing satellite (ERS-2). The spectral resolution of this instrument suits our needs. The GOME instrument has the resolution $\sim$0.33 mm in the oxygen A-band. This allows to obtain approximately 60 measurement points in the spectral range 758–771 mm. The spatial resolution is, however, very poor (typically, $40 \times 320 \text{ km}^2$). It means that the selection of a pixel completely covered by clouds is not a very easy task. Indeed, we need to avoid broken cloud cases. Fortunately, the GOME makes measurements at the enhanced resolution mode $(40 \times 80 \text{ km}^2)$ 3 times per month. So, we mostly used these rare occasions to see the performance of our technique as applied to experimental data.

We have selected a single GOME pixel with complete cloudiness at 43.23°N, 27.44°W at 12:52 UTC on October 15, 1996 above the Atlantic ocean. The cloud-top height for this pixel was estimated from other measurements as well (see details in [4]). The retrieval for this case is considered in the Section II.

Section III is devoted to the comparison of GOME retrievals with independent data obtained from the Along Track Scanning Radiometer-2 (ATSR-2) based on infrared measurements. The ATSR-2 and GOME instruments are on the same space platform. However, they have different spatial resolution and different orientation of footprints. In particular, ATSR scans along a satellite track and has a capability of dual viewing with the spatial resolution 1 km^2. So, the comparison should be considered as a qualitative one. However, it does provide us with the valuable information. This is due to the fact that the cloud-top altitude usually does not change very much for extended cloud fields.
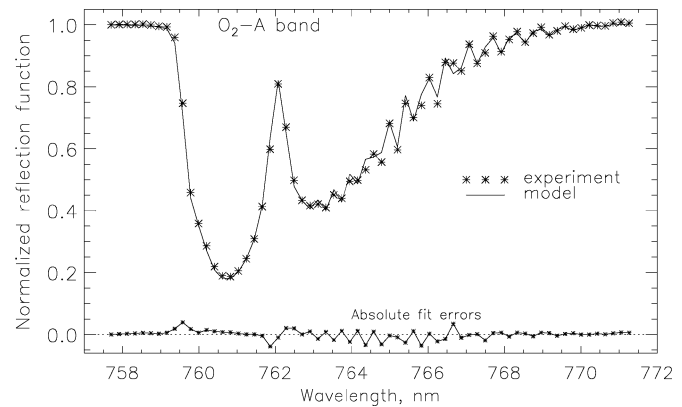

Fig. 1.   Normalized spectral reflection function $R(\lambda)$ in O$_2$ A-band measured by the GOME instrument (symbols). The size of the pixel is $40 \times 320 \text{ km}^2$. Measurements have been performed at 12:52 UTC on October 15, 1996 above the Atlantic ocean (43.23°N, 27.44°W). The solar and observation angles are equal to 53° and 0°, respectively. Solid line denotes calculated results.

II. APPLICATION OF THE SACURA TO GOME DATA: A SINGLE-PIXEL STUDY

In this section we use a simplified version of the SACURA based on the one-parameter retrieval algorithm (see details in Appendix). This allows us to show the dependence of the retrieved cloud-top height on the geometrical thickness and to demonstrate that the geometrical thickness can be evaluated as an additional parameter.

A. Determination of the Cloud-Top Height Using Experimental Reflectance Spectra

Let us derive the cloud-top altitude from the reflectance spectrum $R(\lambda)$ measured by the GOME in the spectral interval 758–771 nm (O$_2$A-band) over Atlantic Ocean. The measured reflectance spectrum normalized by the value $R^* = R(758\,\text{nm})$ is shown in Fig. 1 by symbols. We see that the absorption in A-band is much more stronger than outside of the band . As a matter of fact, the reflectance in the center of the oxygen band for a clear sky case is almost zero. It is around $0.2R^*$ in the case studied. This gives us a clear indication that a cloud field did present in the field of view of the instrument during the time of measurements.

The same GOME cloudy pixel has been already studied in respect to the cloud-top height determination by de Beek *et al.* [4]. However, they used another spectral region (392–395 nm) and a different retrieval technique (Ring effect). They report that the cloud top has been located at 7 ± 1 km for the case studied. De Beek *et al.* [4] confirmed this finding using independent infrared measurements by Meteosat, recorded at 12:00 UTC on October 15, 1996 with account for the temperature measurements of a balloon radiosonde, launched by the research ship Polarstern at 42°N and 35°W at 10:18 UTC on the same day. So, we are pretty sure in the value of h for the case studied.

According to the GOME cloud coverage data, the pixel studied was completely covered by clouds. Therefore, the SACURA should be applicable in this case. Before starting the retrieval algorithm, we need to define some cloud and atmospheric parameters.

So, we use the value of the cloud optical thickness τ obtained from the measurements in the visible $(\tau = 27.7)$ in the assump-
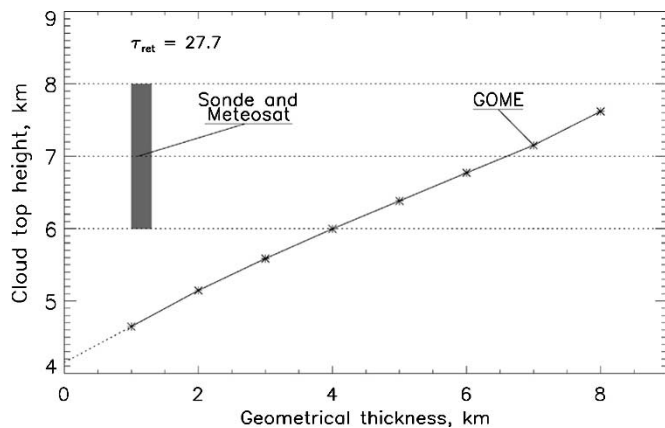
Fig. 2. Ilustration of the retrieval of the cloud-top height and the cloud geometrical thickness from the measured GOME spectra given in Fig. 1. The extrapolation of the results to $l = 0$ is shown with dotted line.

Fig. 3. Dependence of the cost function normalized to its value at $l = 1$ km on the cloud geometrical thickness.

tion that the vertical profile of the liquid water content (LWC) is constant. Also here and below we assume that ice particles do not present in clouds studied and the droplet size distribution is given by the Cloud C1 distribution [5] with the effective radius of droplets equal to 6 μm. The atmospheric aerosol model coincides with that used by Kokhanovsky and Rozanov [11].

The cloud geometrical thickness l is not known *a priori*. Therefore, we estimated the value of h for a number of discrete values of l ranging from 1–8 km with the step 1 km. The dependence of the retrieved value of h on the geometrical thickness l is shown in Fig. 2. We see that this dependence is well pronounced and close to the linear function. It follows from Fig. 2 that the retrieved value of h increases with l. This can be easily understood. Indeed, larger values of the geometrical thickness of a cloud lead to larger light absorption by a cloud. It means that the increase in the value of l leads to the more pronounced minimum of the modeled reflectance spectrum. The depth of the band is fixed, however. It is obtained from measurements. Therefore, to fit measurements for larger values of l, the algorithm produces larger values of h and, therefore, less absorption above cloud. This effect is clearly seen in Fig. 2. The obtained result shows that for accurate retrieval of the cloud-top height we need to estimate the effective cloud geometrical thickness.

It is reasonable to take as such an estimation the value of l, which provides the best correspondence of measured and modeled spectra. The cost function (see the Appendix) is quantitative measure of such a correspondence. Therefore, we must choose a pair (h, l), which provides the minimum of the cost function.

The dependence of the cost function on the geometrical thickness is shown in the Fig. 3. We see that the cost function reaches a minimum for l equals to 7 km. Using data shown in Fig. 2, we find that the corresponding value of h is equal to 7.2 km. So, the solution is the pair (7.2 km, 7 km) for the case studied.

Fig. 1 gives the comparison of the measured and calculated spectra in the oxygen A band. Results of calculations correspond to $h = 7.2$ km and $l = 7.0$ km found from the retrieval technique. Close coincidence of calculations and measurements is found. Therefore, the application of the radiative transfer equation with these values of pair (h, l) (together with derived value
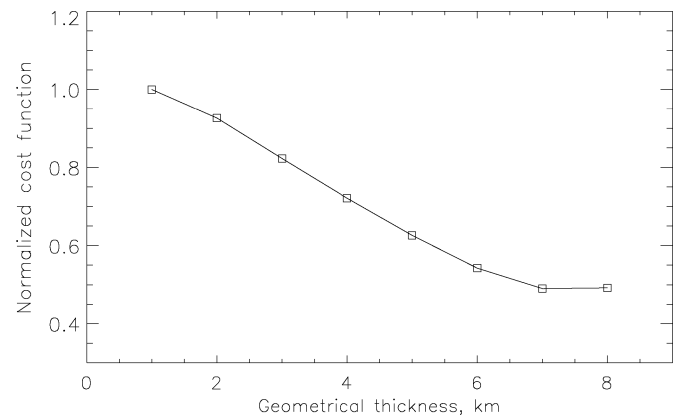
of $\tau = 27.7$) can explain the experimentally measured spectrum quite well.

The obtained result is worth to be discussed in more details. Using the retrieved value of l and the value of the cloud optical thickness given above, we can estimate the mean cloud extinction coefficient. The cloud extinction coefficient defined as the ratio τ/l is equal to ~ 4 km^{-1} for this case. This value is unrealistically low. This leads us to the conclusion that a single homogeneous layer model used in the retrieval is not representative for the case studied.

Although the retrieved value of the cloud-top height agrees well with independent retrievals from other techniques, this could be a result of a pure coincidence. Therefore, more retrievals should be done to establish the technique presented here. Then, independent measurements of h should be also performed. Unfortunately, such measurements (e.g., using laser systems) are rare.

Figs. 1–3 justify our algorithm for the cloud-top height determination. However, the problem of uniqueness of the solution arises. Indeed there is a probability that such a good coincidence of satellite measurements with the data obtained from the radiative transfer theory as shown in Fig. 1 can be achieved assuming that the cloud layer is not uniform in the vertical direction (but, probably, for other values of h, l). Actually, for most of cases of extended cloudiness one or more cloud layers may exist.

B. Retrieval of Cloud Top-Height Using Synthetic Reflectance Spectra for a Two-Layered Cloud System

To check the assumption on the multilayer structure of the cloudiness in the observed scene, we have decided to perform a numerical experiment. To model the situation, we have used the synthetic reflection function obtained for a two-layered cloud system (in the assumption that both layers (see Fig. 4) are composed of water droplets with the constant liquid water content) in our retrieval algorithm for a single homogeneous cloud case. Then, the technique based on the A oxygen band was applied. Note that the upper layer is located at heights 5–8 km, and the lower level cloud extends from 2 until about 3 km above the ground surface.

Fig. 4 shows the retrieved values of h for an effective homogeneous cloud for geometrical thicknesses in the range 1–7 km. The retrieved value of τ coincides with the sum of values of τ
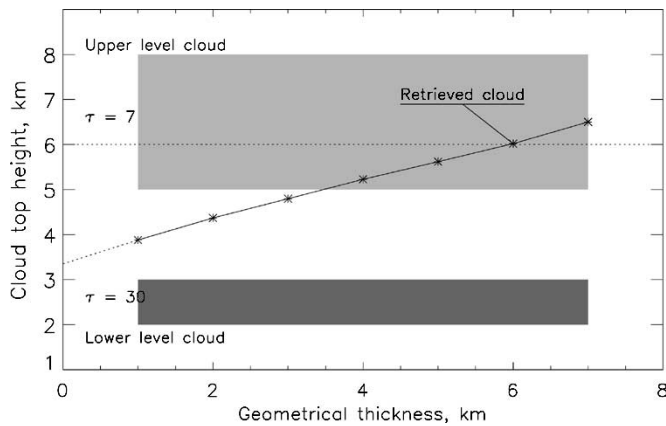
Fig. 4. Illustration of the retrieval of the cloud-top height and the cloud geometrical thickness from simulated data for a two-layered cloud system. The optical thickness of the upper cloud is 7. The optical thickness of the lower cloud is 30. The solar and observation angles are equal to 53° and 0°, respectively. Upper cloud is positioned between 5 and 8 km. The lower cloud layer is located between 2 and 3 km. The extrapolation of the results to $l = 0$ is shown with dotted line.
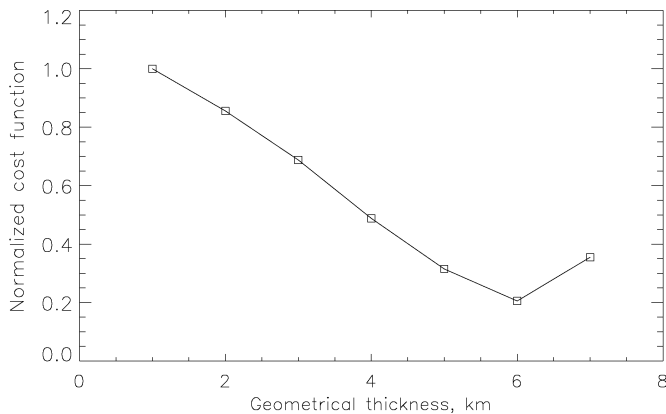

Fig. 5. Dependence of the cost function normalized to its value at $l = 1$ km on the cloud geometrical thickness for the simulated data.

of upper and lower layer ($\tau = 37$). It follows from Fig. 4 that the dependence $h(l)$ closely follows that for the case given in Fig. 2, where experimental spectra are treated.

The dependence of the cost function on the value of l is given in Fig. 5. The minimum of the cost function is reached at $l = 6$ km. The depth of the minimum of the cost function is much more pronounced than it was in the case of experimental spectra (see Fig. 3). The reason is that the synthetic spectra have been used in the case given in Fig. 5.

Using data shown in Fig. 4 we find that corresponding value of h equals to ∼6 km for $l = 6$ km. We see that the retrieved uniform cloud has the geometrical thickness equal h. Taking into account that $\tau = 37$ we find that the effective cloud extinction coefficient is ∼ 6 km^{-1}. This is similar to our finding for experimental data, where also values of h and l were almost identical. Also we had too low values of cloud extinction coefficient in that case.

Comparing obtained cloud-top height with the "true" value (see Fig. 4), we see that the retrieved value of h is lower by 2 km.

All modern cloud retrieval algorithms based on the O_2A absorption band ignore the influence of the cloud geometrical

thickness on the retrieval. Our results show that this leads to the bias in the retrieved values of the cloud-top height. In particular, it follows from Fig. 4 that $h(l = 0) = 3.4$ km (see dotted line in Fig. 4). Therefore, neglecting the value of l, we obtain the value of h, which is by 4.6 km lower than the actual value of $h = 8$ km (see Fig. 4). So, using l as an additional retrieval parameter, we can estimate the cloud-top height more than two times better than in in the case if we neglect the absorption of light inside cloud.

Similar extrapolation of the dependence $h(l)$ given in Fig. 2 to $l = 0$ gives the value of h equal to 4.1 (instead of 7.1, as it follows from infrared Meteosat measurements, Ring effect, and our retrievals with account for the value of l).

The numerical experiment performed supports our idea that a multilayered cloud system existed in the moment of measurements given in Fig. 1. Note that the obtained result is in a good agreement with the data of retrieval of h and l for two-layered cloudy media, which is given in the theoretical study performed by Rozanov and Kokhanovsky [24]. However, in the last case, solar zenith angles and cloud layers optical thickness were different from the case studied here.

The large value of the retrieved cloud geometrical thickness for two-layered cloudy media can be explained as follows. The absorption of photons in a two-layer system occurs not only in the upper and lower clouds but also in the space between them. This is due to the multiple light scattering and radiative transfer from one cloud layer to another. The total light absorptance of the whole system is clearly larger than the sum of the light absorptances of both layers. The value of l in our model is a kind of a regulator of the absorptance level in a cloud. Therefore, the overestimation of l (e.g., l coincides with the distance from the cloud top to the ground surface or even to the level which is below this surface) could be a result of the presence of multi-layered clouds in the scene under study. The retrieval technique, however, is applied to the case of a single homogeneous cloud layer. Therefore, unrealistically large values of l retrieved may indicate that the real situation in the atmosphere does not resemble the assumptions we made in the retrieval scheme. The retrieval of large values of l (e.g., larger than h) is an indicator of a multilayered cloud system.

The discussion presented above show that measurements in the oxygen A-band can reveal information on the vertical distribution of water in cloud systems. This possibility is worth of exploration in future research.

III. COMPARISON OF CLOUD-TOP ALTITUDE RETRIEVALS OBTAINED USING THE OXYGEN A-BAND TOA REFLECTANCE MEASURED BY THE GOME AND THE INFRARED MEASUREMENTS OF THE ATSR-2

We were concerned with the retrieval of the cloud-top height for a single (but previously well-studied [4]) cloudy scene in the previous section. Now we move to the application of our algorithm to selected cloudy pixels from several GOME orbits. The results of our retrievals are compared with independent data from ATSR-2 instrument located at the same satellite as the GOME spectrometer. The brightness temperatures of cloudy pixels as measured by ATSR-2 are routinely used to obtain cloud-top pressures (and heights). The European Center for
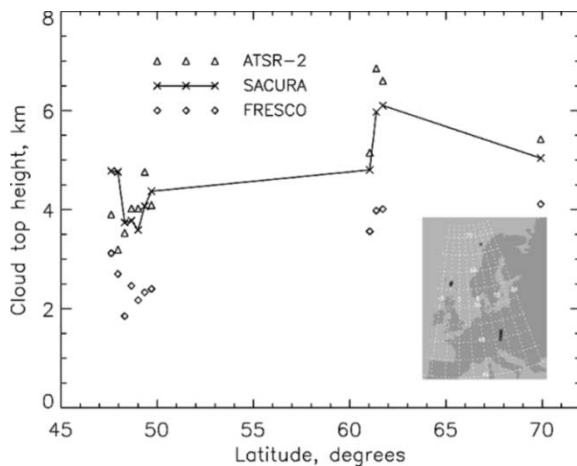
Fig. 6. Cloud-top height retrieved from GOME (FRESCO, SACURA) and ATSR-2 data for selected pixels from orbits 50 723 095 and 50 723 114 of the ERS-2 (July 23, 1995), having cloud cover close to 1.

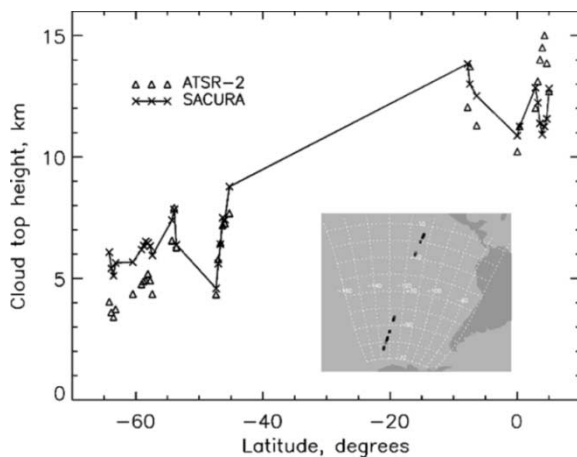Fig. 8. Scatter plot of data given in Fig. 6.

Fig. 7. Cloud-top height retrieval from GOME (SACURA) and ATSR-2 data for selected pixels from the orbit 80 324 174 of the ERS-2 (March 24, 1998), having cloud cover close to 1. The pixel positions are shown on the map.

Medium-Range Weather Forecasts (ECMWF) model (ECMWF 1995, the description of the ECMF/WCRP Level III-A Global data Archive) is applied to increase the accuracy of such a conversion. The coincidence of retrievals confirm that both methods are at least consistent. The disagreement shows that at least one of the methods produces wrong results.

Selected results of our retrievals as compared to the ATSR-2 data are given in Figs. 6 and 7 for scenes located both over land and ocean. We assumed in the retrieval that the albedo of ocean is equal to 0.05 and that of land is equal to 0.3. Although the assumed albedo of the land can be biased as compared to a "true" surface albedo, the influence of the surface on the top-of-atmosphere reflectance is low for pixels studied (cloud optical thickness is larger than 35).

Note that the spatial resolution of the ATSR-2 differs from that of GOME. Therefore, we averaged the ATSR-2 data to bring them in correspondence with the spatial resolution of GOME. Only enhanced resolution (40×80 km^2) GOME pixels completely covered by clouds were taken for the comparison.

The retrieval technique, which is used in this Section is slightly different from that applied in Section II. In particular,
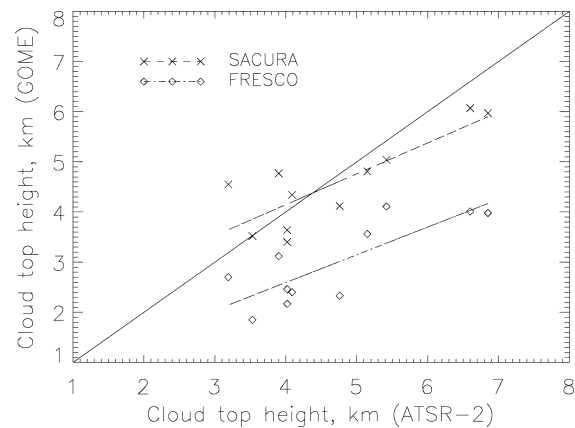
we derive the pair (h, l) simultaneously from the condition of the minimum of the cost function using reflectance spectra in the O$_2$ A-band (see the Appendix). We did not apply the technique based on the simultaneous retrieval of the pair (h, l) in the previous section because the retrieval method based on the derivation of h at the fixed value of l gives us more insights in the peculiarities of the retrieval algorithm as used in interpretation of measurements. This was a major issue studied in Section II.

Generally, we find that the agreement of results obtained using both instruments is quite good. In particular, both retrieval techniques show smaller cloud-top heights as moving from the equator to the north (see Fig. 7), which is a well-known effect related to the change in the position of the tropopause with latitude. There are disagreements, however (see in particular, Fig. 7). Let us consider obtained results in more detail, starting from Fig. 6.

It follows from data given in Fig. 6 that results of the SACURA are inside of error bars (approximately ± 1 km) of the ATSR-2 retrievals. So, both techniques give similar cloud-top heights. This is an encouraging fact.

On the same Fig. 6, we give cloud-top heights obtained using a very similar technique as ours but assuming that the cloud can be substituted by a Lambertian reflector with the albedo 0.8. The correspondent algorithm was developed by Koelemeijer *et al.* [9]. It is called the Fast Retrieval Scheme for Clouds from Oxygen A band (FRESCO). The FRESCO is often used to account for cloudiness in trace gas concentrations retrieval schemes. We see that the SACURA much improves the FRESCO results. This is easily understood. Indeed, we consider the radiative transfer inside clouds, which is not a primary target of the FRESCO, which can retrieve only so-called biased effective cloud-top heights. They are always smaller than actual ones (see Fig. 6). This bias is due to the fact that in reality photons penetrate through a cloud top and are absorbed by oxygen there. This leads to the increase of the oxygen absorption depth even for high clouds. If the process of the photon penetration is neglected (a Lambertian diffuser assumption), then this increased depth of the absorption band is interpreted as an existence of a cloud on a level, which lower that the actual altitude of a cloud. This is confirmed by Fig. 6.
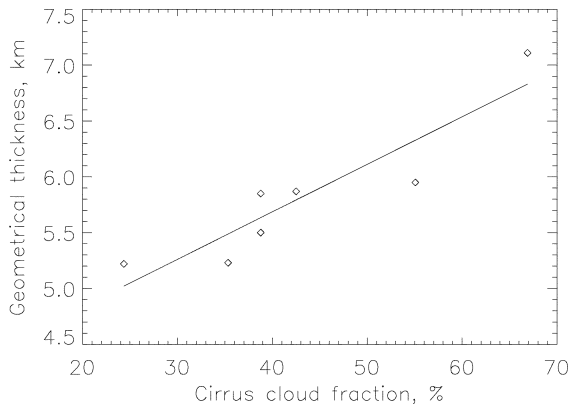
Fig. 9. Dependence of the retrieved value of the cloud geometrical thickness l using SACURA on the value of the cirrus cloud fraction D obtained from ATSR-2 data for the case given in Fig. 6.

Fig. 10. Scatter plot of data given in Fig. 7.

The scatter plot of cloud-top heights obtained with the SACURA and the FRESCO for the case given in Fig. 6 is shown in Fig. 8. We see that the displacement error of the FRESCO algorithm is 1.88 km as compared to 0.13 km for SACURA, if the ATSR-2 data are taken as true data. In reality, however, ATSR-2-derived cloud-top heights may have error up to 1 km and even higher. This should be remembered when performing comparisons as those given in Fig. 8. The root mean square of the cloud-top height data obtained with the SACURA is three times smaller than those for the FRESCO (0.22 against 0.66). Therefore, the example studied shows that the account for the cloud geometrical thickness (even as an effective parameter; see Rozanov and Kokhanovsky [24]) allows to make a reduction of the difference between retrieved cloud-top heights using the ATSR-2 and GOME instruments. Fig. 8 clearly shows limitations of the FRESCO as applied to cloud-top altitude retrievals.

The SACURA also produces as an output the effective cloud geometrical thickness, which gives the best fit of measured and calculated TOA reflectance spectra in the oxygen A-band (see Fig. 1) for a single vertically homogeneous cloud layer. This is a new product, which cannot be derived from ATSR-2. However, as it was shown above (see Figs. 2 and 4 and also the theoretical study of Rozanov and Kokhanovsky [24]), the retrieved value of l is highly dependent on the vertical structure of the cloudiness under investigation. In particular, for multilayered cloud fields, l can become unrealistically large (e.g., $l \geq h$). This is the case for the orbit given in Fig. 6 as well. So, we conclude that most probably multilayered cloudiness has existed in the field of view of the GOME instrument during measurements. To justify this assumption we present the dependence of the retrieved value of l on the degree of the coverage D of the field of view of GOME by cirrus clouds for the case given in Fig. 6. Such clouds often present near the tropopause. The values of D were obtained for this orbit from ATSR-2 data. The dependence of l on D is shown in Fig. 9 by symbols for values of D larger 20%. It follows that the results given in Fig. 9 can be fitted by a linear function. This means that larger values of D lead also to larger values of the retrieved effective geometrical thickness l. This well corresponds to results of Min *et al.* [15]. They show
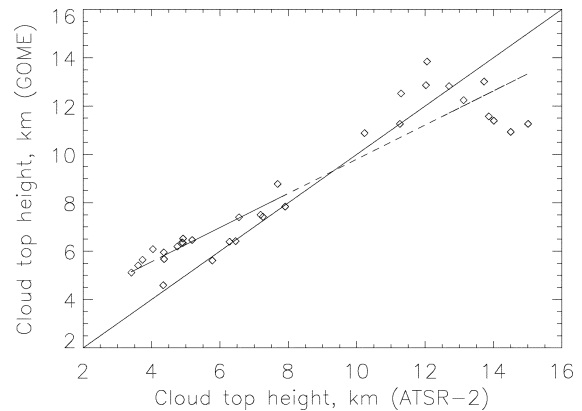
that the average photon path length increases under conditions of multilayered cloudiness. This results in the enhanced absorption of photons in multilayered cloud systems as compared to the case of a single cloud. The main parameter, which regulates the absorption in our model, is l. Therefore, the increase of l with D is an indicator of the absorption enhancement in multilayered clouds.

We would like to underline that not for all cases we find such a good agreement of the SACURA and the ATSR-2 retrieval results as in Fig. 6. The example is shown in Fig. 7, where comparatively large deviations are found (e.g., see pixels close to equator and 60°S latitude). Generally, deviations decrease for cases with $l < h$. For instance, the deviations ζ for pixels located in the range of latitudes 3.2°N to 45.3°S (where $l < h$) are equal to 0.5 km in average as compared to $\zeta = 1.0$ km for pixels located in the range of latitudes 45.3°S to 64.2°S (where $l > h$).

The scatter plot of data given in Fig. 7 is shown in Fig. 10. It follows from Fig. 10 that the largest discrepancy takes place for low and high clouds.

However, we suspect that although all pixels in Fig. 7 are completely covered by cloudiness, main assumptions behind either the SACURA or the ATSR-2 retrieval technique are violated. This may explain the discrepancy found.

In particular, let us consider pixels in the vicinity of the equator (see Fig. 7), where the SACURA gives too low values of h. This can be explained by the fact that cloud altitudes are highly variable near the equator. So, the assumption of the horizontally uniform layer, used by the SACURA is violated in this area for large GOME pixels (even for the case of 100% cloudy pixels). Then, measurements of h with the GOME instrument become inadequate. Our guess is supported by the ATSR-2 data given in Fig. 7 (the points close to right vertical axis), which show a high variability in a cloud-top height on a small spatial scale. We also retrieved the cloud optical thickness for this area using algorithm described by Kokhanovsky *et al.* [12]. The value of the cloud optical thickness varies in the range 17–107 on the distance of approximately 80 km. This confirms our guess that the cloud field considered is highly inhomogeneous in the horizontal direction. Therefore, we face here problems not related to the SACURA itself but to the GOME spatial resolution.
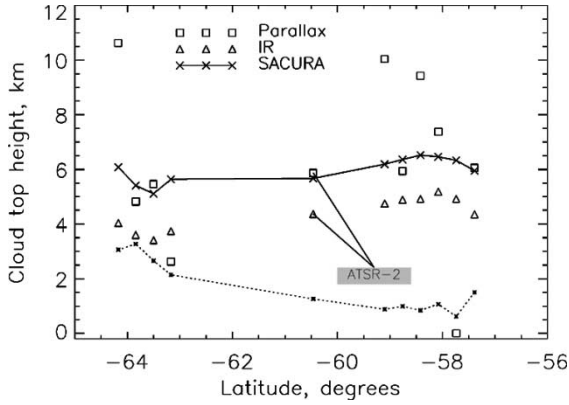
Fig. 11. Dependence of retrieved cloud-top height on latitude obtained using different retrieval techniques and optical instruments onboard the ESR-2. SACURA/GOME results are given by the solid line with crosses. Parallax and infrared ATSR-2 techniques are shown by symbols. The dashed line shows the dependence of the geometrical thickness excess $(l - h)$ on the latitude. Results for the infrared ATSR-2 technique and the SACURA/GOME retrieval coincide with those given in Fig. 7 around $60°$S.

Let us consider now the disagreement of retrievals close to the $60°$S latitude (see Fig. 7). The discrepancy between values of h obtained from the GOME and the ATSR-2 is around 2 km in this region. Whether this is due to the failure of the SACURA, the ATSR-2 retrieval technique or both remains unclear. However, we would like to underline that generally the accuracy of the infrared ATSR-2 cloud-top height retrieval technique decreases for low-level clouds (especially if cirrus clouds are present in the scene). Then, the error of the infrared technique can reach 2 km [19], which can explain the discrepancy found.

The comparison between GOME SACURA and ATSR-2 infrared and parallax [21] techniques is given in Fig. 11 for the region $\sim 60\,S$. Note that data for SACURA/GOME and infrared ATSR-2 technique coincide with those given in Fig. 7. The parallax technique uses the dual-viewing capability for the same scene. It gives values of h that differ from those obtained both from cloud brightness temperature measurements performed by ATSR-2 and from SACURA results for this particular case.

Let us underline that the retrieved effective geometrical thickness l is larger than h for the cases studied. To illustrate this fact, we show the geometrical thickness excess $\xi = l - h$ in Fig. 11 for latitudes $57°$ to $65°$S. Note that ξ is positive and reaches 3.5 km at $64°$S. This points again to the fact that the multilayered cloudiness probably existed in the field of view of the detector, and the assumption of a single homogeneous cloud layer used in the retrieval procedure is most probably wrong.

IV. CONCLUSION

We presented here the first application of the SACURA to the determination of the cloud-top height h and geometrical thickness l using the TOA reflectance measurements in the oxygen A-band. The algorithm is relied upon the semianalytical solution of the radiative transfer equation, which is valid for single homogeneous clouds having optical thickness larger than 5.

Using the experimental and simulated reflectance spectra in the O_2 A-band, we have shown quantitatively the dependence of the retrieved value of h on the geometrical thickness of clouds l. We have demonstrated that parameters h and l can be re-

trieved from the measured reflectance spectra in the oxygen absorption band simultaneously (in the assumption of a homogeneous layer). This is similar to findings reported by Daniel *et al.* [3], who used, however, not only oxygen A-band but also other oxygen absorption bands (along with absorption bands of the O_2–O_2 collision complex).

We have found unrealistically large values of the retrieved geometrical thickness $(l > h)$ for most cases studied. Our theoretical study shows that such large retrieved values of l underline the fact that a multilayered cloudiness existed in the field of view of the instrument during measurements.

Unfortunately, the direct measurement of the vertical structure of the cloudiness studied is not available to us. Nevertheless, the found relationship between retrieved values of l and the degree of the coverage of the field of view of the GOME by cirrus clouds points out that our assumption is quite reasonable.

Although results obtained as far as the value of l is concerned are of a limited value, we believe that we can identify the cases with multilayered cloudiness.

The new information which can be derived from the reflectance spectra in the oxygen A-band is not very significant in the case of such large ground pixels as that by GOME $(40 \times 80 \text{ km}^2$ in the best case). Then, the multilayered structure of cloudiness is quite probable to occur. But our technique could be of importance for future spaceborne optical instruments including the Orbing Carbon Observatory.

The large retrieved values of l enable us to reach coincidence between the measured and simulated A-band spectra of the real-world multilayered cloud systems and a single homogeneous layer model. Therefore, the retrieved cloud-top height is more realistic comparing with other techniques, which completely neglect multiple light scattering in the cloud itself or account for multiple light scattering using fixed value of the cloud geometrical thickness.

The comparison of the obtained cloud-top height with other results as retrieved from infrared ATSR-2 and METEOSAT measurements shows that our algorithm is capable to give the cloud-top height similar to these popular techniques. The discrepancy is smaller than 1 km for the most cases.

APPENDIX
INVERSE PROBLEM SOLUTION

The theoretical basis of the SACURA is given by Rozanov and Kokhanovsky [24]. However, for the sake of clarity and completeness, we summarize the main steps of the inverse problem solution here.

A. Linearization of the Reflectance

Fist of all, the TOA reflectance R is presented in the form of a Taylor expansion around the assumed value of the cloud-top height equal to h_0

$$R(h) = R(h_0) + \sum_{i=1}^{\infty} a_i (h - h_0)^i \qquad (1)$$

where $a_i = R^{(i)}(h_0)/i!$. Here $R^{(i)}(h_0)$ is the i-derivative of R at the point h_0. The next step is the linearization, which is a stan-

dard technique in the inversion procedures [22], [23]. We found that the function $R(h)$ is close to a linear one in a broad interval of the argument change [11]. Therefore, we neglect nonlinear terms in (1). Then, it follows that

$$R(h) = R(h_0) + R'(h_0)(h - h_0) \qquad (2)$$

where $R' = (dR/dh)$. We assume that R is measured at several wavelengths in the oxygen A-band. Then, instead of the scalar quantity R, we can introduce the vector $\vec{R}_{\mathrm{mes}}$ with components $(R(\lambda_1), R(\lambda_2), \ldots, R(\lambda_n))$. The same applies to other scalars in (1).

Therefore, (2) can be written in the following vector form:

$$\vec{y} = \vec{a}x \qquad (3)$$

where $\vec{y} = \vec{R}_{\mathrm{mes}} - \vec{R}(h_0)$, $\vec{a} = \vec{R}'(h_0)$, and $x = h - h_0$. Note that both measurement and model errors are contained in (3).

B. One-Parameter Retrieval Algorithm

The solution $\hat{x}$ of the inverse problem is obtained by the minimizing the following cost function [22]:

$$\Phi = \|\vec{y} - \vec{a}x\|^2 \qquad (4)$$

where $\| \;\|$ means the norm in the Euclidean space of the correspondent dimension.

The value of $\hat{x}$, where the function Φ has a minimum can be presented as

$$\hat{x} = \frac{(\vec{y}, \vec{a})}{(\vec{a}, \vec{a})} = \frac{\displaystyle\sum_{i=1}^{n} a_i y_i}{\displaystyle\sum_{i=1}^{n} a_i^2} \qquad (5)$$

where $(,)$ denotes a scalar product in the Euclidean space, and n is the number of wavelengths, at which the reflection function is measured.

Therefore, knowing the measured spectral reflection function R_{mes} and also the calculated reflection function $R(h_0)$ and its derivative $R'(h_0)$ at several wavelengths, the value of the cloud-top height can be found from (5) and equality $h = \hat{x} + h_0$. The value of h_0 can be taken equal to 1.0 km, which is a typical value for low-level clouds.

The reflection function of the cloudy atmosphere depends not only on the value of h but also on l in the oxygen absorption band. In particular, l is a major parameter that determines the level of light absorption in cloud in the oxygen absorption band. Therefore, the value of $\hat{x}$ depends on the assumed cloud geometrical thickness l_i. Accordingly, the cost function $\Phi(h(l_i))$ $(h(l_i) = \hat{x}(l_i) + h_0)$ depends on the choice of l_i as well.

The cost function at a given argument l_i characterizes the degree of the coincidence of the model and the experiment for the derived value of $\hat{x}(l_i)$. Therefore, it is natural to take as retrieved values of the cloud geometrical thickness and cloud-top height those values for which $\Phi(h(l_i))$ reaches a minimum.

The algorithm of the determination of values h and l is reduced, therefore, to the choice of l_i $(i = 1, \ldots, N)$, the estima-

tion of $\hat{x}(l_i)$ for each l_i in correspondence with (5) and the determination the value of i, which insures that $\Phi(h(l_i)) \to \min$.

The technique described above is used for the solution of the problem under consideration in Section II.

C. General Retrieval Technique

In Section III, both values of h and l are found simultaneously. This requires the minimization of the following cost function [see (4)]:

$$\Phi = \|\vec{y} - \hat{A}\vec{X}\|^2. \qquad (6)$$

The elements of the matrix $\hat{A}$ are correspondent weighting functions [22]. The solution of the inverse problem is given by the vector-parameter $\vec{X}$. This vector has five components in our case, which give corrections to the initially assumed cloud-top height and cloud geometrical thickness, the correction to the initially assumed half-width of the spectrometer spectral response function, the shift parameter, and the squeeze parameter.

Clearly, the first two parameters give us final values of the pair (h, l) to be retrieved. The third parameter allows to adjust the assumption on the instrument response function. The last two parameters allow the reduce errors related to the displacement of the experimentally measured spectrum due to the errors of the spectral calibration.

We have developed two versions of the retrieval algorithm. One is based on the exact radiative transfer calculations of the reflection function R, and another one is based on the approximate representation of R by the following equation:

$$R = R_0 + T_1 R_c T_2 \qquad (7)$$

where R_0 gives the reflection function of the part of atmosphere above the cloud, R_c is the cloud reflection, and functions T_i $(i = 1, 2)$ give transmission coefficients from the sun to a cloud and from the cloud to a satellite, respectively. Approximate equations for all functions in (7) are given elsewhere [11]. Note that we have used the retrieval technique based on the approximate representation of R [see (7)] in this paper. It allows to speed up the retrieval process considerably.

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